RESEARCH ARTICLE

Resolution characteristics of optical coherence tomography for dental use

¹Hiroshi Watanabe, ¹Ami Kuribayashi, ²Yasunori Sumi and ¹Tohru Kurabayashi

¹Department of Oral and Maxillofacial Radiology, Graduate School, Tokyo Medical and Dental University, Tokyo, Japan;

²National Center of Advanced Medicine for Dental and Oral Diseases, National Center for Geriatrics and Gerontology, Obu, Japan

Objectives: The purpose of this study was to clarify the resolution characteristics of optical coherence tomography (OCT) for dental use.

Methods: Two types of swept-source optical coherence tomography machines were employed in this study. To clarify their resolution characteristics, we newly developed a glass chart device with a ladder pattern of wavelengths, which ranged from $4 \times 2 \mu\text{m}$ to $1024 \times 2 \mu\text{m}$, as well as a star-target pattern, a grid pattern and a spatial frequency response pattern. The resolving powers and characteristics of the OCTs were subjectively evaluated.

Results: The Santec OCT-2000™ (Santec Co., Komaki, Japan) had a resolving power of $64 \mu\text{m}$ in both the horizontal X and vertical Y directions, while the OCT from Yoshida had a resolving power of $64 \mu\text{m}$ in the horizontal X direction and $128 \mu\text{m}$ in the vertical Y direction. The resolving power of the depth Z direction could not be obtained from this study. With the Yoshida OCT, the star-target pattern seemed to be non-symmetrical, owing to an edge enhancement effect, which was revealed when the ladder patterns were placed in a horizontal direction.

Conclusions: This study successfully clarified the resolution characteristics of two types of OCTs. The obtained data may be useful for diagnostic purposes, and the glass chart device used in this study may be useful for OCT quality assurance programmes.

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Introduction

Optical coherence tomography (OCT) is a new non-invasive modality that delivers cross-sectional images using near infrared light. OCT is already widely used by ophthalmologists, and it may be useful in diagnosing several retinal diseases.¹ High-resolution tomographic images are a speciality of OCT, and they enable observation of living objects in real time at micrometre

levels.² This technology was recently introduced into the dental field and some prototype machines have been developed. Potentially useful applications of these machines have been reported such as in the assessment of caries, enamel cracks, periodontal gingiva status and material defects.^{3–7} OCT is generally said to have a high spatial resolution, which can detect more detailed structures without any radiation exposure. This technology is expected to be commercially available for dental clinical use. However, there have been no studies concerning the concrete image resolution delivered by OCT. It may be important to understand resolution characteristics for the diagnostic process and quality assurance programmes.

Correspondence to: Dr Hiroshi Watanabe. E-mail: hiro.orad@tmd.ac.jp

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Figure 1 The appearance of the two optical coherence tomography (OCT) units: the box area represents the body of the OCT, which is composed of a light source, an interferometer, a personal computer for analysis and a display monitor. The arrows indicate the probe.

Therefore, we developed a glass chart device that enables us to ascertain the resolving powers and characteristics. The aim of this study was to evaluate resolution characteristics of OCTs for dental use.

Methods

Optical coherence tomography units

Two prototype swept-source optical coherence tomography machines were employed in this study: the Santec OCT-2000™ (Santec Co., Komaki, Japan)^{3,5} and the Yoshida OCT (Yoshida Dental Mfg. Co., Ltd, Tokyo, Japan). The appearance of two OCT units was shown in Figure 1. Both machines were developed independently, but are based on the same frequency domain OCT technique that measures the magnitude and time delay of reflected light in order to construct a depth profile. With the Santec OCT, the centre wavelength is set to 1319 nm with a scan range of 112 nm at a 20-kHz sweep rate and with the Yoshida OCT, the centre wavelength is set to 1310 nm with a scan range of 140 nm at a 50-kHz sweep rate. The specifications of both OCT units are summarized in Table 1 and the nominal resolutions (*X*, *Y* and *Z*) are presented. The focused light beam is projected onto the selected location and scanned across the cross-sectional plane of interest using a handheld probe. Backscattered light from the object is coupled back to the system and digitized in a time scale and then analysed in the Fourier domain to reveal depth information from the object, which can be reconstructed as two-dimensional images. The system can acquire two-dimensional serial sections as three-dimensional (3D) scans.

Glass chart slide

To investigate the resolution characteristics of OCTs, we developed a new glass chart device in concert with FUJIFILM Imaging Systems Co., Ltd. (Tokyo, Japan). Chrome evaporation was performed with a 1.0-μm-

thick layer on 2.3-mm-thick soda lime (70–74% silicon dioxide, 0–3% aluminium oxide, 6–12% calcium oxide, 0–6% magnesium oxide and 12–16% sodium oxide) with a 6-mm square pattern, as shown in Figure 2. The patterns were composed of a ladder pattern at 4, 6, 8, 12, 16, 24, 32, 64, 128, 256, 512 and 1024 μm, a ladder pattern with continuously changing ladder thickness from 1024 μm to 4 μm, a star-target pattern, a 20-μm-width grid pattern and a spatial frequency response (SFR) pattern with a 4° inclination. The bar pattern accuracy was within ±0.3 μm.

Acquisition of image data and analysis of the data

The glass chart slide was used to test two OCT units. The slide was placed on a desk and the handheld probe was placed vertically on the slide. With the Santec OCT-2000, the 3D acquisition mode was used, the field of view (FOV) was set to 8 square mm and voxel numbers of *X*, *Y* and *Z* were set to 512, 512 and 100, respectively. As a result, the voxel size was 15.6 × 15.6 × 7.5 μm. The obtained data were exported as tagged image file format files with a 3D data converter for INNER VISION (Santec). With the Yoshida OCT, the FOV size could be selected from 6, 8 or 10 square mm and the depth could be selected from 4 mm or 8 mm, although voxel numbers were fixed at 400 × 400 × 1024 (4-mm depth) or 400 × 400 × 2048 (8-mm depth). We selected the minimum 6-mm FOV and the shorter 4-mm depth; thus, the voxel size was 15 × 15 × 3.9 μm. The obtained data were exported as digital imaging communications in medicine (DICOM) files using a Dental OCT DICOM converter (Yoshida). The exported data were processed in ImageJ64 v. 1.43u software (<http://rsb.info.nih.gov/ij/>) run on a Macintosh computer (Apple Inc., Cupertino, CA), and *XY* views of the slices were created. With the Yoshida OCT, the data were obtained as coronal views of the slide, and they were imported in ImageJ 64 as sequential images and resliced as *XY* views. The *XY* views of both OCTs were averaged with Image > Stacks > Z projection function. The averaged *XY* images were used for observation. The images were evaluated by two observers (HW and AK, with 18 and 13 years' experience as oral radiologists, respectively) on a 17-inch liquid crystal display (EIZO FlexScan S190, Ishikawa, Japan) in a dim room. The observations were performed independently; any disagreement between them was resolved by discussion and a consensus was reached.

Table 1 The specifications of Santec OCT (Santec Co., Komaki, Japan) and Yoshida OCT (Yoshida Dental Mfg. Co., Ltd, Tokyo, Japan)

OCT unit	Santec OCT	Yoshida OCT
Central wavelength (nm)	1319	1310
Scan range (nm)	112	140
Scan rate (kHz)	20	50
Resolution (<i>X</i>) (μm)	37.3	35
Resolution (<i>Y</i>) (μm)	37.3	35
Resolution (<i>Z</i>) (μm)	11.4	11

Figure 2 The patterns of the glass chart device: No. 1–12—the rectangular ladder patterns of 4, 6, 8, 12, 16, 24, 32, 64, 128, 256, 512 and 1024 μ m, which correspond to No. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12, respectively. No. 13: the ladder pattern continuously changes in thickness from 1024 μ m to 4 μ m. No. 14: the star-target pattern. No. 15: the 20- μ m-width grid pattern. No. 16: the spatial frequency response pattern with a 4° inclination. All the patterns have a size of 6 square mm, supposing the field of view of the optical coherence tomography to be approximately the same size. The bar pattern accuracy is within $\pm 0.3 \mu$ m.

Results

The glass chart was successfully scanned by two OCTs. The star-target patterns are shown in Figure 3. With the Santec OCT, the pattern had point symmetry, but with

the Yoshida OCT, the pattern was partially collapsed in a horizontal direction near the centre. Figure 4 shows the continuous ladder patterns. In both OCTs, the fifth thinnest white ladder bar could be seen and the profiles of the image were confirmative when the ladder pattern

was placed vertically (Figure 4a and b). However, when the pattern was placed horizontally (Figure 4c and d), the Yoshida OCT provided an edge enhancement image as shown in Figure 4d, in which only the fourth thinnest white ladder bar could be seen. Figure 5 shows the SFR image. The Santec OCT showed a smooth edge, while the Yoshida OCT showed some enhanced edges. When the ladder patterns were observed (Figure 6), the 64- μm -width ladder could be resolved in the Santec OCT image, and the 64- μm -width ladder in the horizontal direction and the 128- μm -width ladder in the vertical direction could be resolved in the Yoshida OCT image. The chart had a 20- μm -width grid pattern, but the grid appeared to be too small to be observed in both OCTs.

Discussion

OCT is anticipated for dental practices because of its higher resolution.^{3–7} Machines for dental OCT have been developed by several groups^{5,6,8–10} and will be commercially available in the near future. Swept-source optical coherence tomography was recently introduced and its centre wavelength was set to nearly 1300 nm, which focuses on the enamel for its high coefficient transmission. Each article described the above-mentioned lateral and depth (or axial) resolutions and according to Santec and Yoshida, the lateral resolutions were said to be 37 μm and 35 μm , respectively, and the depth resolution was 11 μm in air. However, these values are theoretical and the only way to measure the effective resolutions is directly on the images. Hence, we developed the new glass chart device and measured the practical resolution characteristics of OCTs in this study.

The figure of the star-target revealed that the Santec OCT provides a point symmetrical image, but the Yoshida OCT presented an edge-enhanced image for the bars located in a horizontal direction (Figure 3), which became clearer in the ladder image located in two different directions (Figure 4). Such edge enhancement effects were observed in the SFR image (Figure 5) and the ladder images (Figure 6). These observations suggest that the chart device may be employed for specific image processing computations, and it is important to consider these characteristics when interpreting the OCT images.

From the observations on the ladder pattern images, the lateral resolution of the Santec OCT was found to be 64 μm , and the horizontal and vertical resolutions of the Yoshida OCT were 64 μm and 128 μm , respectively (Figure 6). The numbers of the ladder pattern were discrete and the observation was subjective; therefore, to know more precise resolution powers, it may be better to order the ladder patterns in each unit from 32 μm to 128 μm for these OCTs or to develop a method for computing modulation transfer function (MTF) as an objective evaluation.⁹ However, there exist

Figure 3 An image of the star-target pattern: Santec OCT (Santec Co., Komaki, Japan) (left) depicted the pattern to be point symmetrical, but with the Yoshida OCT (Yoshida Dental Mfg. Co., Ltd, Tokyo, Japan) (right), the star-target pattern was partially collapsed in a horizontal direction near the centre (arrows).

several dental OCTs^{6–8} whose theoretical resolutions ranged extensively from 6 μm to 36 μm in the lateral direction, where it would be essential to make the slide covering the range above. Concerning MTF measurements, we tried to obtain a line or point spread function; however, the OCT images have too much noise as shown in the figures to obtain a stable MTF result. If the theoretical lateral resolution of Santec and Yoshida OCTs were reported to be 36 μm and 35 μm , respectively, the results of this study would be almost confirmative. The potential differences between the theoretical and the surveyed values may be due to lens strain, a stain, focus depth, existence of a Fourier transformation method, image filters, or image voxel sizes. These factors are fixed when a machine is designed and manufactured, but there are some factors, such as a lens stain or laser power output, which would change with the passage of time. The devices in this study may be useful to monitor the status of OCT machines, allowing the user to maintain machine performance during routine use.

Although the device could clarify the lateral resolutions of two OCTs, it is not suitable for depth resolution. OCT depicts images from the coefficient of transmission information of an object; therefore, depth length and optical path would depend on the object optical properties.¹⁰ The device in this study was created by the chrome evaporation technique on slide glass; thus, no signal was obtained behind the chrome. Therefore, it is not applicable for depth evaluation. A new technique to visualize depth resolution or to compute MTF for depth direction is needed.

In summary, the two types of OCTs studied in this study could differentiate 3D structures between 64 μm and 128 μm .^{4,5} This is superior to CBCT, which could only distinguish approximately 300 μm .¹¹ Indeed, the enamel cracks could be observed to the same extent as with a confocal laser scanning microscope⁴ or micro-

Santec OCT

A

Yoshida OCT

B

C

D

Figure 4 The image of the continuous ladder pattern: on the Santec OCT (Santec Co., Komaki, Japan) images (a and c), the fifth white bar could be seen in either image when the ladder pattern was placed vertically (a) or horizontally (c). On the Yoshida OCT (Yoshida Dental Mfg. Co., Ltd, Tokyo, Japan) images (b) and (d), the fifth thinnest white bar could be seen when the ladder pattern was placed vertically (b); but, when the pattern was located horizontally (d), there is an edge enhancement with the bars and only the fourth thinnest white bar could be seen.

Figure 5 Images of spatial frequency response (SFR) pattern: SFR was the pattern with a 6 mm square and a 4° inclination, which could reveal image properties concerning a depicted edge. The Santec OCT (Santec Co., Komaki, Japan) (left) showed the edge of SFR to be smooth, but the Yoshida OCT (Yoshida Dental Mfg. Co., Ltd, Tokyo, Japan) (right) showed that the edges were relatively enhanced.

CT,⁵ and the gingival sulcus could be precisely measured without using a physical pocket probe.⁶ In addition, OCT could reflect the difference of transmission information and detect demineralization of teeth,^{7,10,12,13}

which only a visual inspection would be able to find. However, OCT has a limitation, as it is not able to observe the deeper region because of short penetration of the infrared light.^{3,6}

Conclusions

In this study, we developed a new glass chart slide to clarify OCT resolution characteristics. As a result, we could clarify the differences between two OCT units and evaluate their resolving limitations in *XY* dimensions. This tool may be useful to evaluate resolution characteristics of OCTs and to execute appropriate quality assurance programmes for OCTs.

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Disclosure of Conflict of Interest

We declare that there is no conflict of interest with regard to this study.

Figure 6 Images of the ladder patterns: the ladder patterns were visualized by the two optical coherence tomography (OCT) machines, located in horizontal and vertical directions. With the Santec OCT™ (Santec Co., Komaki, Japan), the 64-μm-width ladder could be resolved irrespective of the directions. With the Yoshida OCT (Yoshida Dental Mfg. Co., Ltd, Tokyo, Japan), the 64-μm-width ladder could be resolved in the horizontal direction, but only the 128-μm-width ladder could be resolved in the vertical direction.

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